Structural Analysis of a Scientific Balloon Using Assumed Strain Formulation Solid Shell Finite Elements

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Motivation & Objective

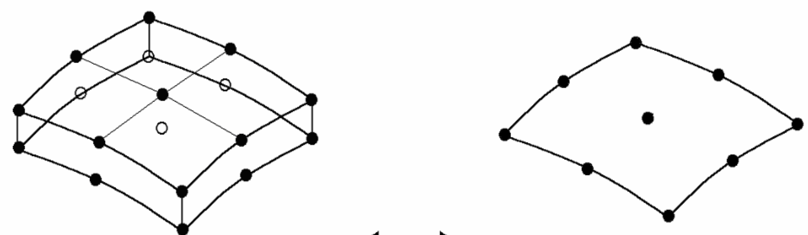
- Structural analysis of gossamer structures is challenging due to their extreme flexibility:
  - The effective range of length-to-thickness ratio (**L/t**) and radius-to-thickness ratio (**R/t**) for assumed strain solid shell formulation must be determined.

- To investigate applicability of quadruple precision assumed strain formulation solid shell elements to gossamer structures.
  - Solar sail ribbons under their own weight.
  - Wrinkling formation in a square membrane.
  - Shapes and stresses of an ascending scientific balloon.

Assumed Strain Solid Shell Formulation

- Assumed strain formulation to avoid element locking
  - Strain field independent of displacement, eliminated at element level
- Solid shell formulation
  - Treats shells as 3D solids: transverse shear/extension deformation
  - Kinematic variables in a vector form: no angles

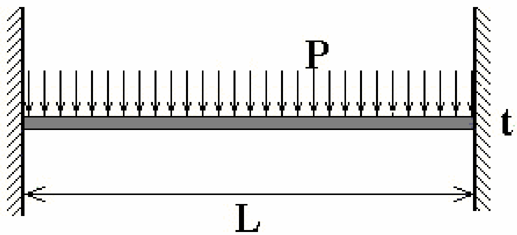
- 54-dof elements



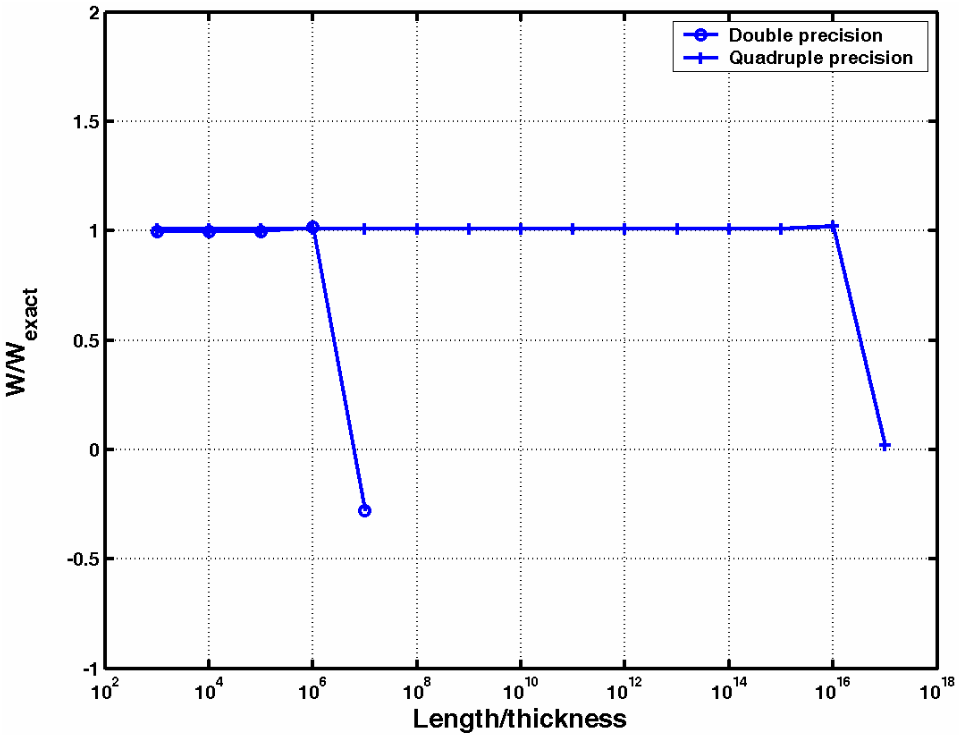
18-node version
3 dof/node

9-node version
6 dof/node

Shear Locking Test

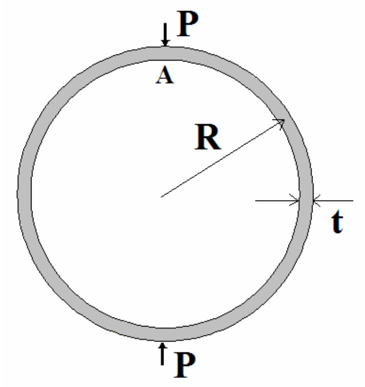


- Clamped beam subjected to pressure **P**
- Flat structures (varying **t**)
- Geo. Linear tests to determine the effective range of **L/t**

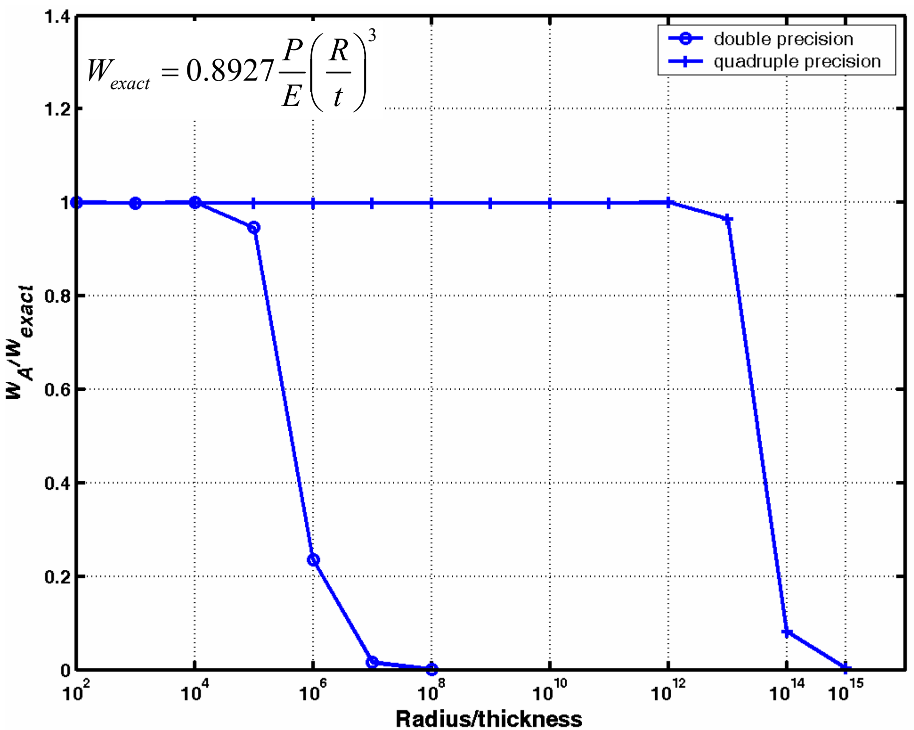


- Effective range of **L/t**
  - Double precision: Max $L/t = 10^6$
  - Quadruple precision: Max $L/t = 10^{16}$

Membrane Locking Test

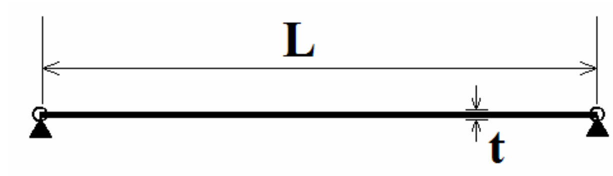


- Pinched ring ($\mathbf{R}$=100 m)
- Thin curved structures (varying $\mathbf{t}$)
- Geo. Linear analysis to determine the effective range of $\mathbf{R/t}$



- Effective range of $\mathbf{R/t}$
  - Double precision: Max $\mathbf{R/t} = \mathbf{10^4}$
  - Quadruple precision: Max $\mathbf{R/t} = \mathbf{10^{12}}$

Solar Sail Ribbons



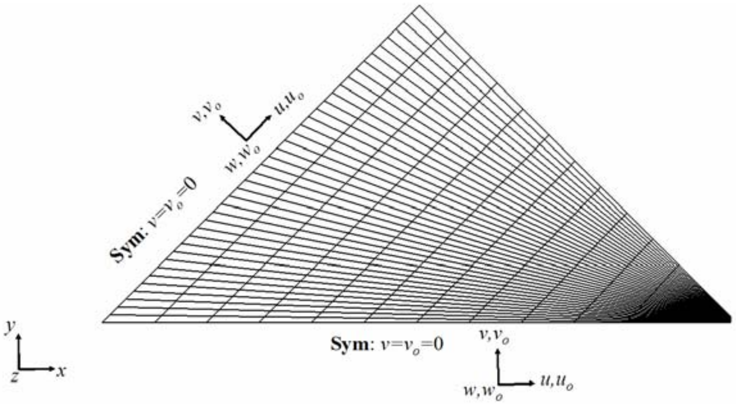
- Geometry of pinned ribbons: L=(100 m, 1 km, 10 km), t=10^{-6} m
- Material: Kapton (E=2.6 GPa, ν=0.3, ρ=1420 kg/m^3)+
- Geo. nonlinear static analysis to determine the deflection under own weight
  - A loading scheme that activates small bending stiffness of membranes is introduced. Weight (P_o=ρgt) applied as $P = P_o \times 10^{-m}, \quad m = 20,15,10,5,0$
  - **No Stabilizing Schemes** (pre-tension/artificial damping/explicit dynamic)

L (m)	t (m)	Mesh	*Exact W_{max}	Analysis W_{max}
10^2	10^{-6}	10x2	-2.927	-2.927
10^3	10^{-6}	10x2	-6.307x10	-6.301x10
10^4	10^{-6}	10x2	-1.359×10^3	-1.354×10^3

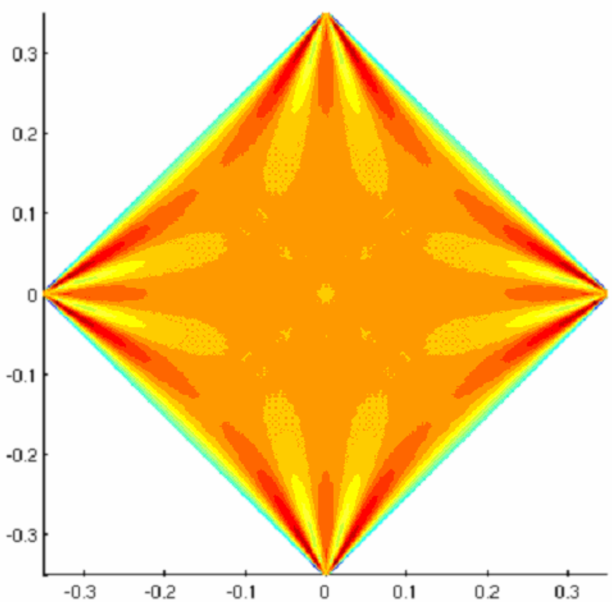
+ Wang, J. T., Chen, T., Sleight, D. W. and Tessler, A., 5th Gossamer Spacecraft Forum, 2004

* Roark, R. J. and Young, W. C., Formulas for Stress and Strains

Wrinkling Formation



- A square membrane: L=0.5, t= 2.54x10^{-5} (m)
- Subjected to tension (2.45 N) at four corners
- Material identical to solar sail ribbons
- Due to symmetry, one eighth with 6x20
- Modeling techniques* adopted
  - elimination of sharp corners
  - corner force replaced by distributed force
  - random out-of-plane imperfections in corners



- Geo. nonlinear static analyses with quadruple precision assumed strain solid shell elements
- **No stabilizing schemes**
- Four wrinkles across corner (Amp: -0.61 ~ 0.25 mm)
- Further study to quantify amplitudes

* Tessler, A., Sleight, D. W. and Wang, J. T., 4th Gossamer Spacecraft Forum, 2003

A Scientific Balloon

- A zero-pressure scientific balloon is considered as follows:

D. Altitude	**37.5 (km)**	W. payload	35.23 (kN)	E. tape (GPa)	2.813
D. Volume	**1.12 (MCM)**	Film density	$1.805 \times 10^3 (kg/m^3)$	E. skin (GPa)	0.301
# of gores	**172**	Tape density	$4.316 \times 10^3 (kg/m^3)$	ν. skin	0.83

- Computational modeling of scientific balloons are challenging due to their extreme flexibility and under-constrained nature.

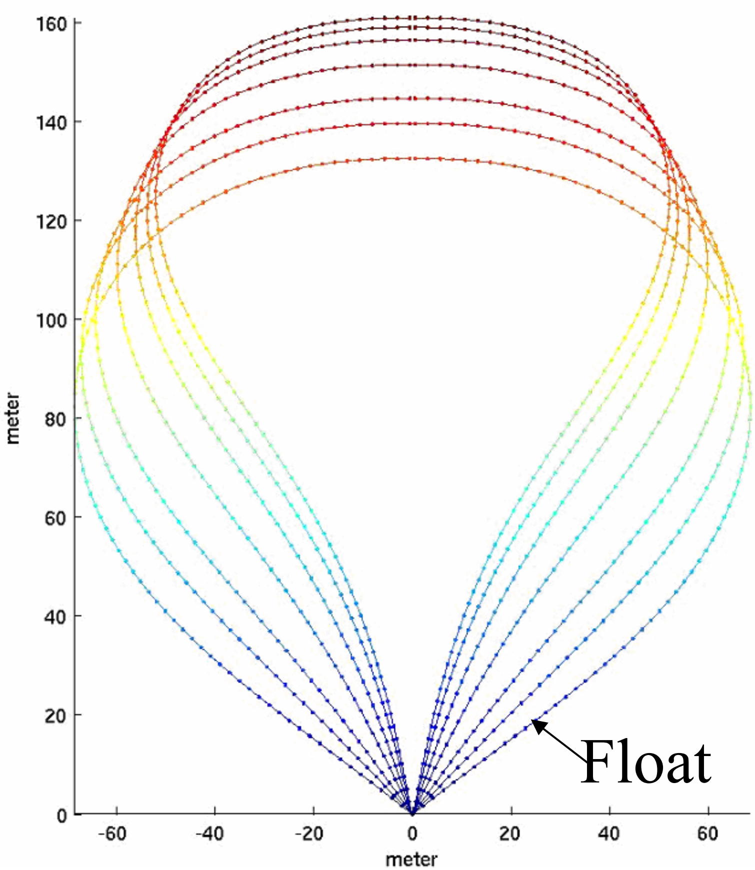
  - Ratio of gore-length to skin-thickness ~ 10^7

  - Quadruple precision required

Gore length	**201.35**	Radius at the apex	0.53
Skin thickness	**2.0×10^{-5}**	Film thickness	5.1×10^{-5}
Film width	5.1×10^{-2}	Radius at the nadir	0.078

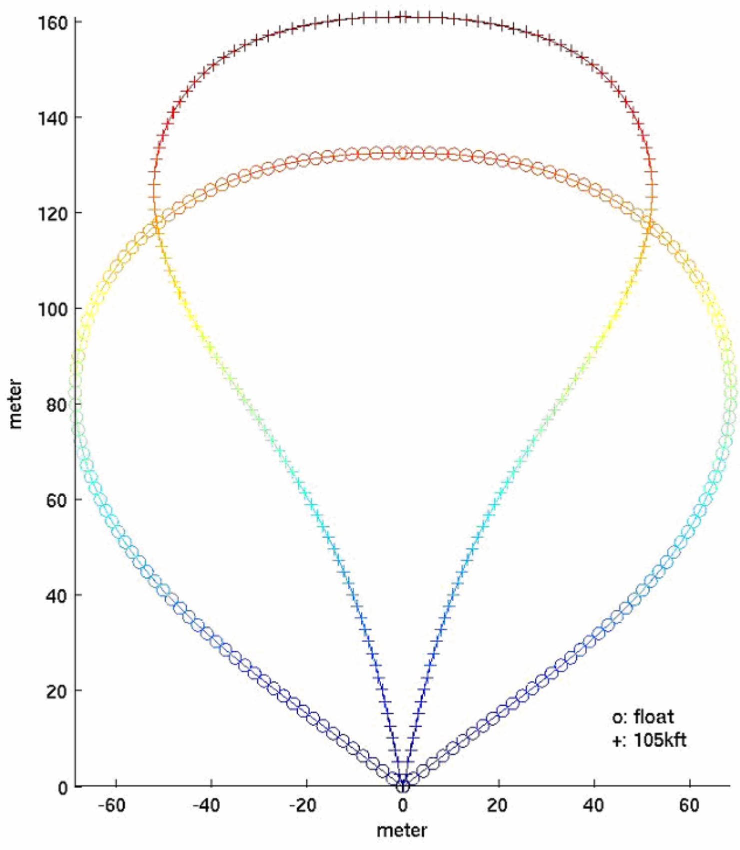
A Scientific Balloon (Cont.)

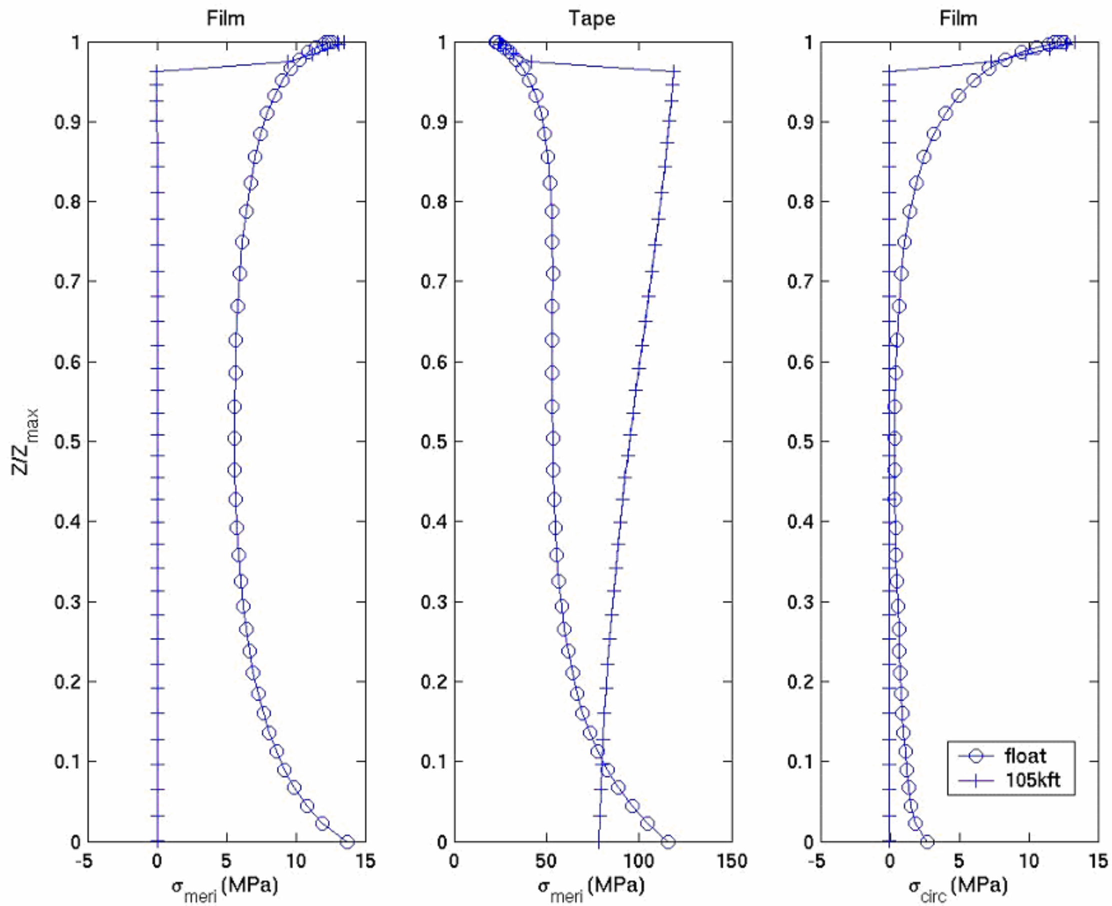
- Buoyancy as lift, equal to sum of the pressure differential across the skin surface over the entire balloon.



- Interdependency of pressure & shape:
  - Shape change depends on pressure.
  - Pressure depends on shape change.
  - Must be simultaneously determined in a repetitive manner
- In addition, payload and distributed material weight considered
- Structural analysis under two primary premises:
  - Rotational symmetry through deployment.
  - Inertia effect ignored
- From the design configuration at float, geo. nonlinear static analysis continues to lower altitudes.

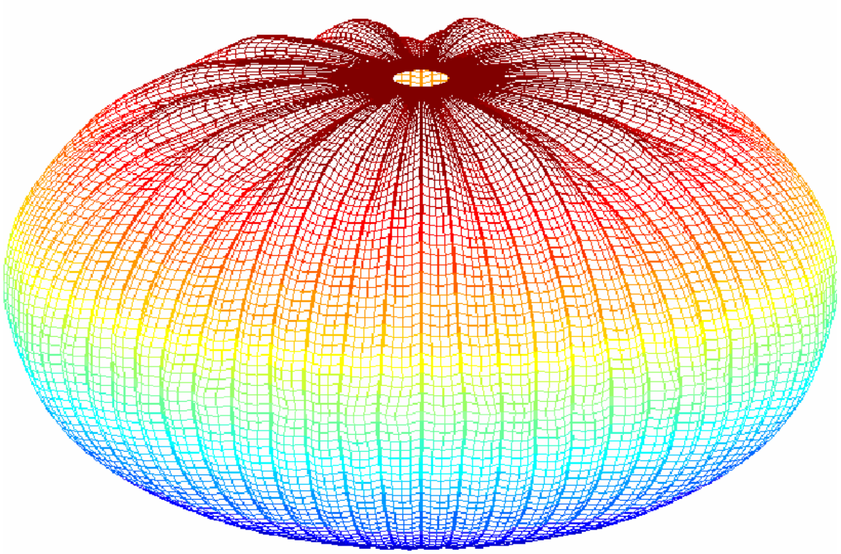
A Scientific Balloon (Cont.)





Conclusions & Future Work

- The effective range of **L/t** and **R/t** increases with quadruple precision for the assumed strain solid shell element formulation.
- The finite element method based on this special formulation provides an efficient analysis tool for gossamer structures such as solar sail ribbons and scientific balloons.



- Stability analysis for

  super-pressure scientific balloons can be carried out using the quadruple precision assumed strain solid shell element formulation.
- A parallel solver has been developed to accommodate increased problem size.